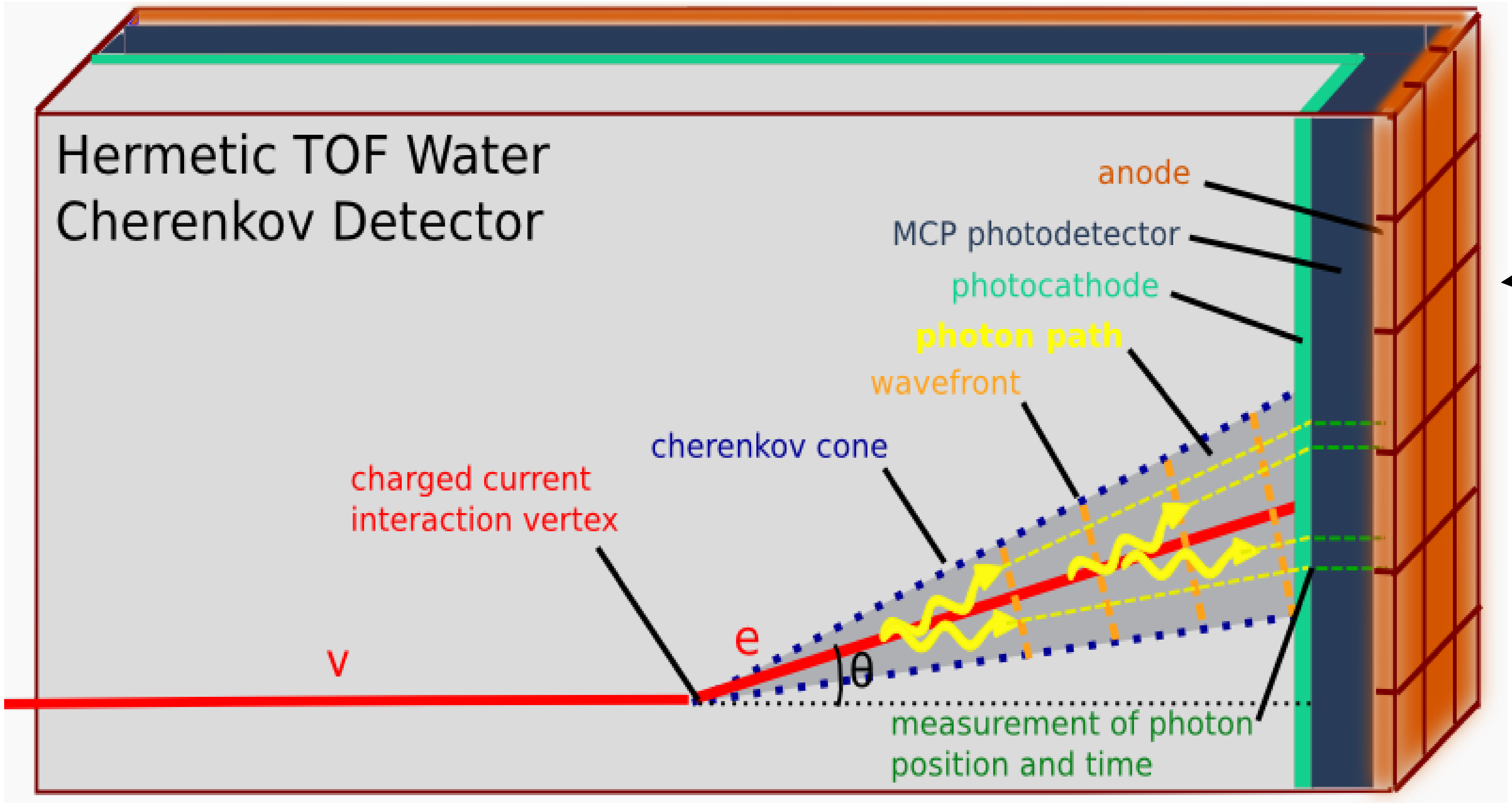
Time of Flight Instrumentation for Project X and Other

Bob Wagner
Argonne National Laboratory
Project X Physics Study
Time-of-Flight Working Group
14 June 2012

Outline

- Applications for Time-of-Flight — Why push timing resolution <100ps, 10ps, 1ps, <1ps
- Extension to wider Science Community
- Detectors (apologizes to missing yours or your favorite)
  - MCP-centric
  - SiPM
  - Gas
- Limitations

Hermetic TOF Water Cherenkov Detector



Tesselation of detector with Large Area MCP-PMTs

talks on Large Area MCP in parallel sessions Sat/Mon by Wetstein & Elagin

Technique: measure arrival time and position of photons and reconstruct tracks in water

Advantages:

1) Smaller volume => lower construct and materials cost
2) Lower cost photodetectors?

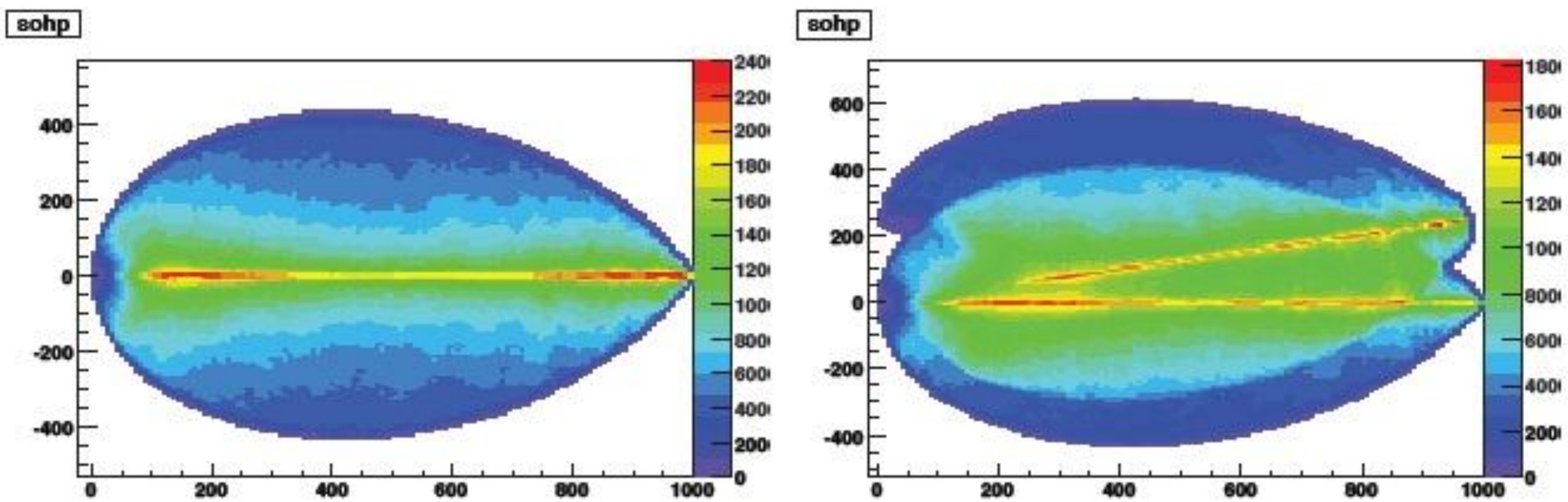
Alternatives: Large PMTs, liquid argon

Photon Tracking Detector

Track Reconstruction Using an "Isochron Transform"

Results of a toy Monte Carlo with perfect resolution

Color scale shows the likelihood that light on the Cherenkov ring came from a particular point in space. Concentration of red and yellow pixels cluster around likely tracks

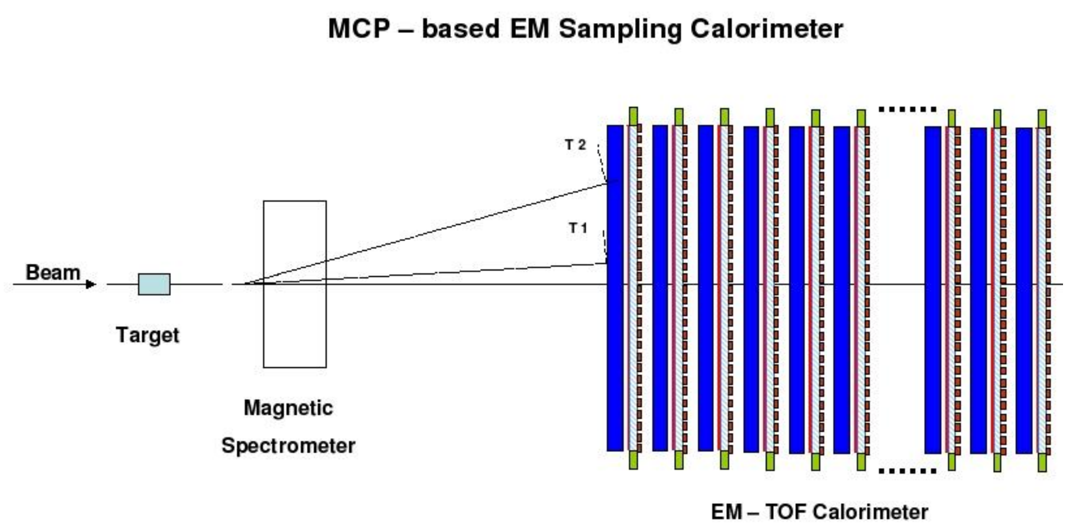


Single track

Two tracks displaced from a common vertex

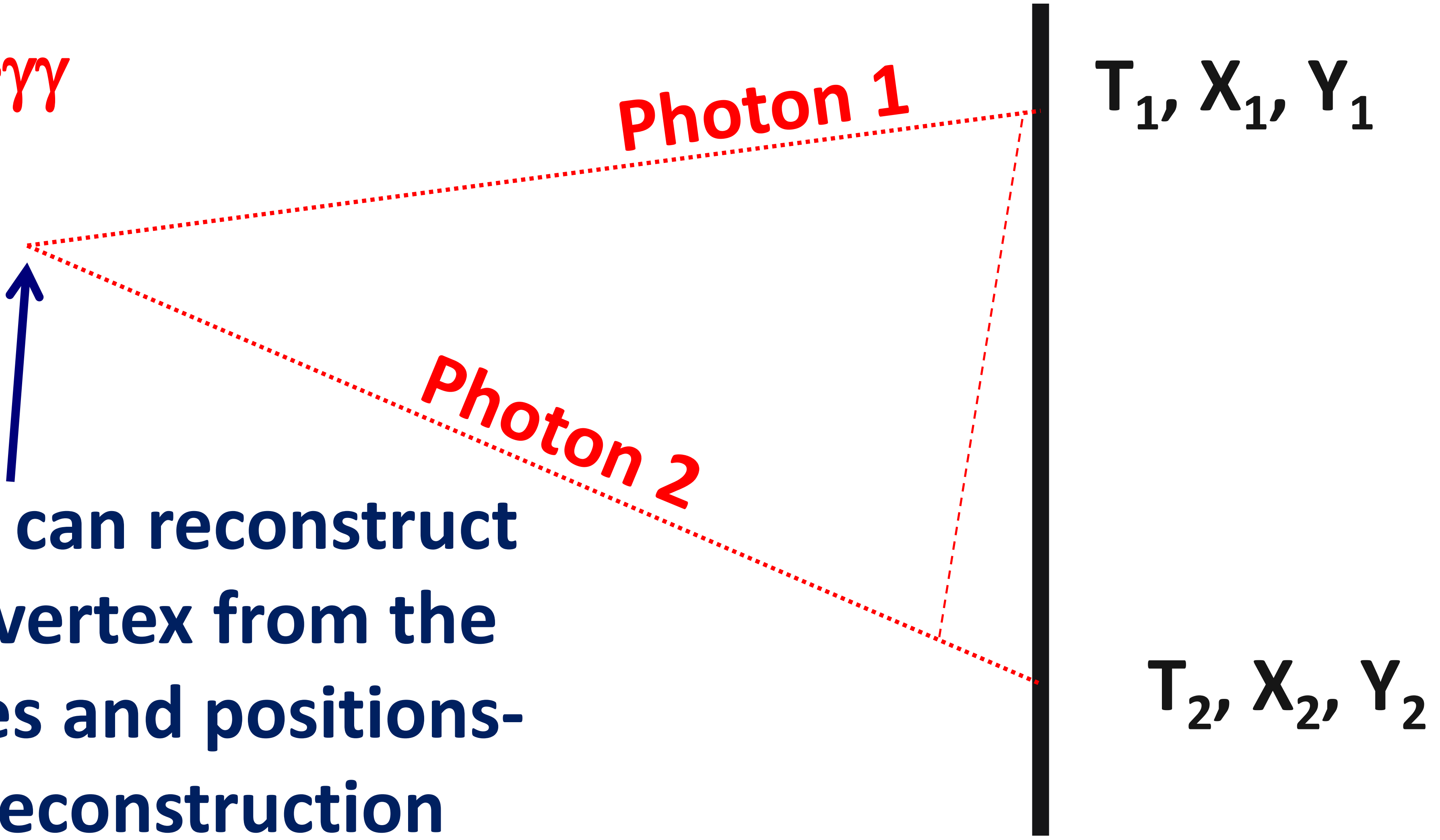
Work of Matt Wetstein - see parallel session talk 18 Jun 2012 Large Area Detector Track

Rare Kaon Decays - $K_L \rightarrow \pi^o \nu \bar{\nu}$



Vertex $\pi^0 \to \gamma\gamma$

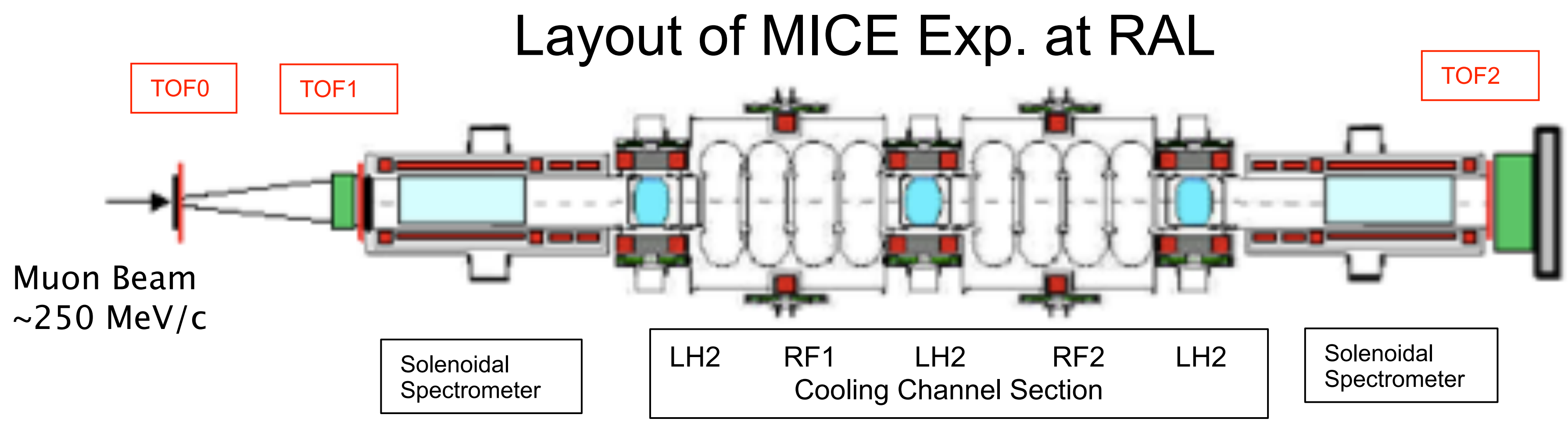
T_v, X_v, Y_v, Z_v



One can reconstruct the vertex from the times and positions- 3D reconstruction

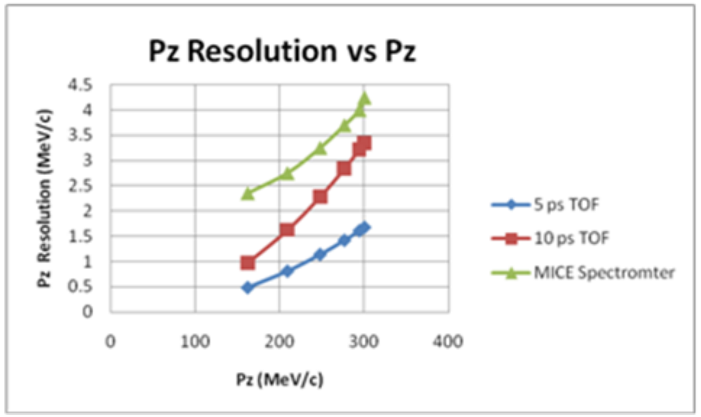
Reduce combinatoric background for π^o

Time-of-Flight for Muon Cooling

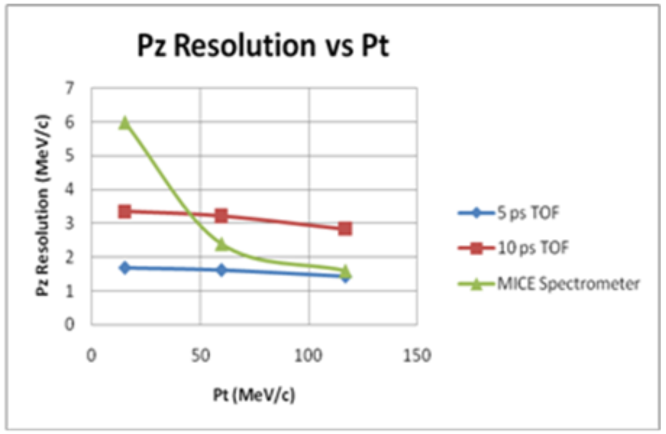


Robert Abrams (Muons. Inc.)
Workshop on Timing Detectors,
Cracow, Nov 2010

- Muon cooling phase space and emittance determination
- TOF was fast scintillator and PMT — 50-60ps resolution, spatial 2-3cm
- Improvements in P_Z resolution for 5-10ps time resolution and <1mm spatial

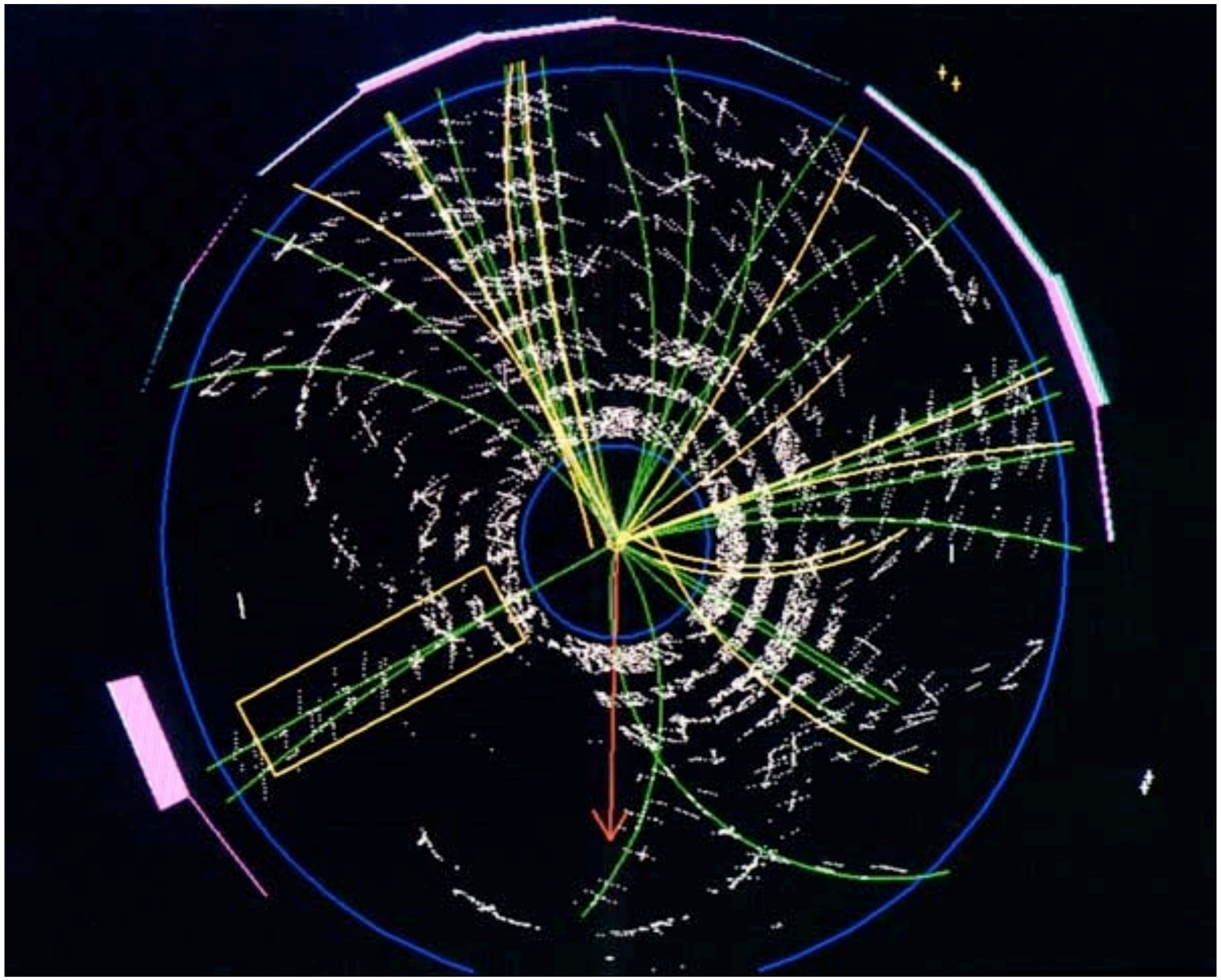


(a)



(b)

Time-of-Flight for Colliding Beam Experiments



Complete particle measurement: E, p + m(PID)
1ps time & 1mm space resolution, $100k/m^2

Goal is to measure ALL information allowing for identification of quarks producing the jets. Requires particle ID for momentum of 10's of GeV/c

Several components contribute to time resolution limit:

- Signal source - absorption, scattering, thresholds
- Detector limits - efficiency, coverage, noise, dispersion
- Electronics - bandwidth, slewing, sampling speed, noise

*Fast Timing detectors for Forward Protons at the LHC**

* LHC = Large Hadron Collider at CERN

Mike Albrow, Fermilab

Need for ~ 10 ps timing: **HPS** = High Precision Spectrometer
AFP = ATLAS Forward Protons
$p + p \rightarrow p + H + p$, $p + W^+W^- + p$, etc…

How to get 10 ps timing: **QUARTIC**s (Gas, Fused Silica) + MCP-PMTs
Q-bars + SiPMs (Silicon Photomultipliers)
Beam tests at Fermilab …. Electronics

Reference time signals

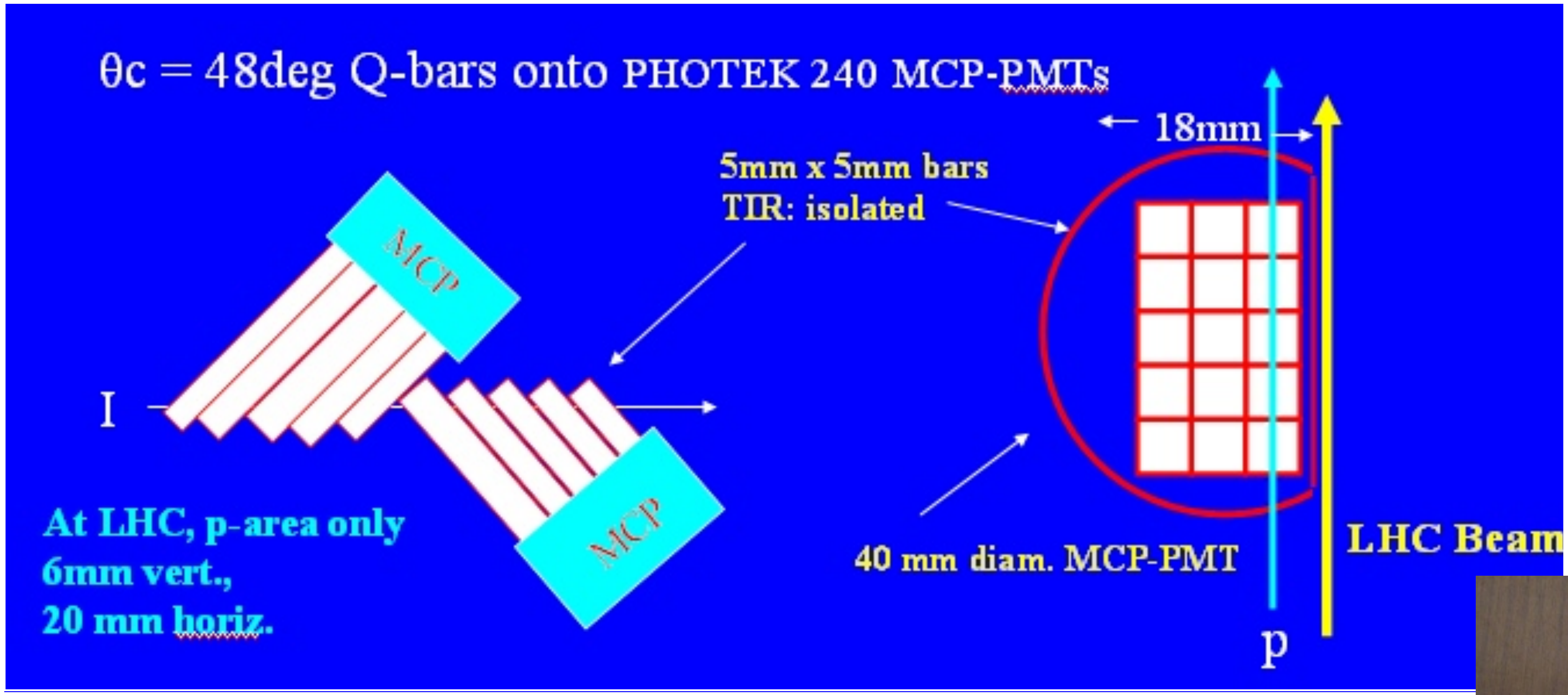
Futuristic: **Forward Discs, Central Barrel, GHz streak camera?**

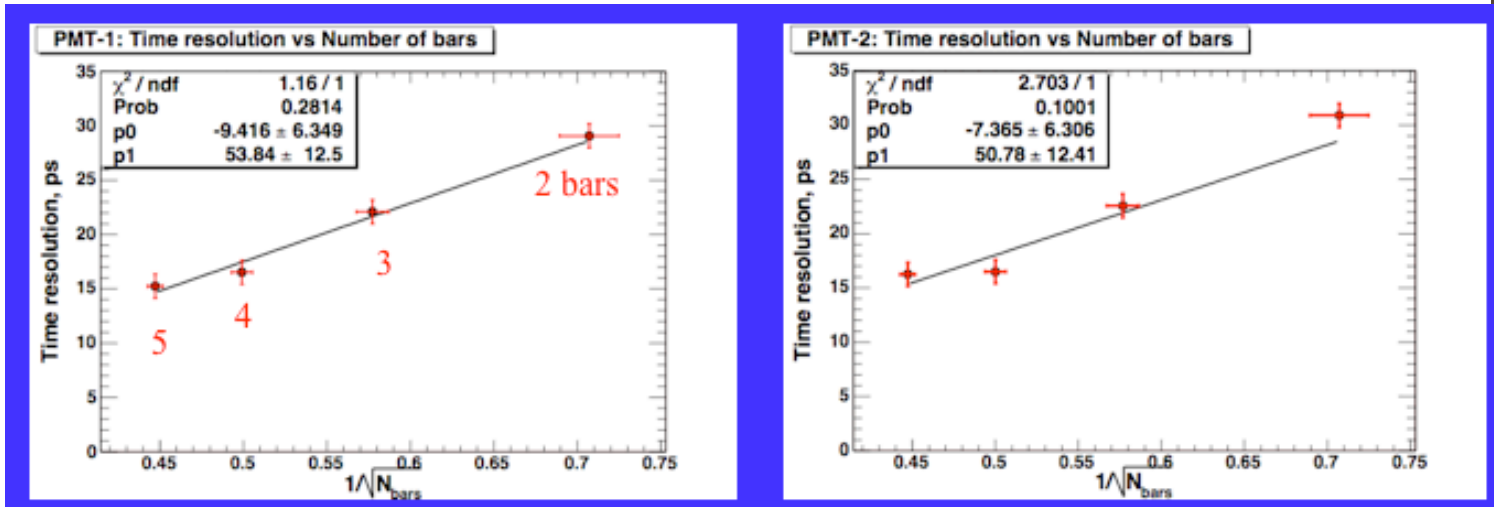
Status HPS, AFP, and plans for timing.

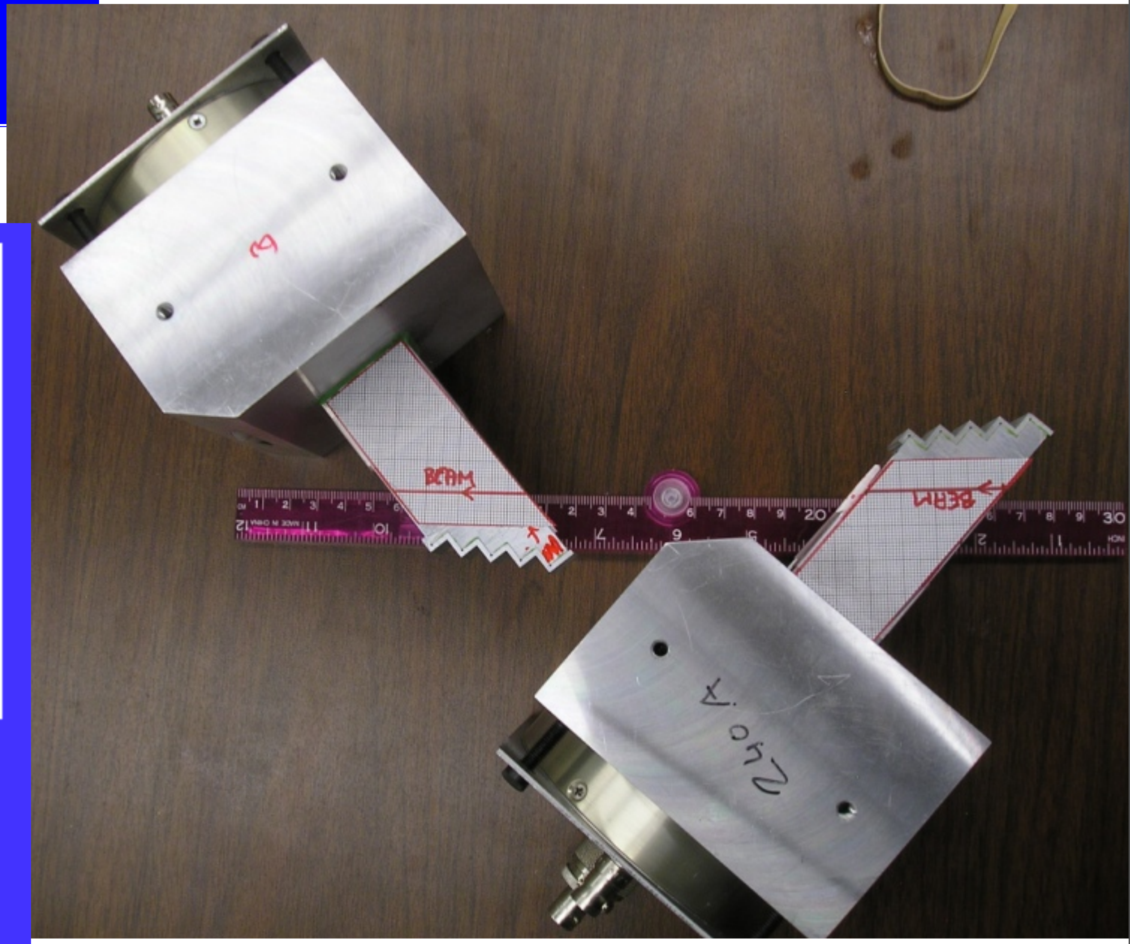
Mike Albrow   Fast Timing Detectors for Forward Protons at the LHC   Cracow Timing Workshop – Dec 2010

talk on QUARTIC in parallel sessions Sat by Mike Albrow

QUARTIC Test Results







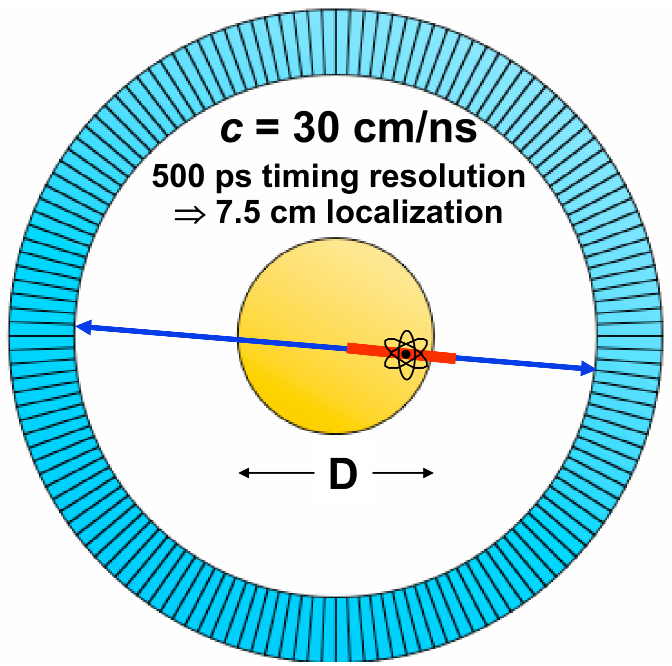
$$\sigma(t) \approx \frac{1}{\sqrt{N(bars)}}$$

→Bars contribute about equally
→Two detectors the same

p.e. ~ 20-25 (5 bars)

Time-of-Flight for PET Imaging

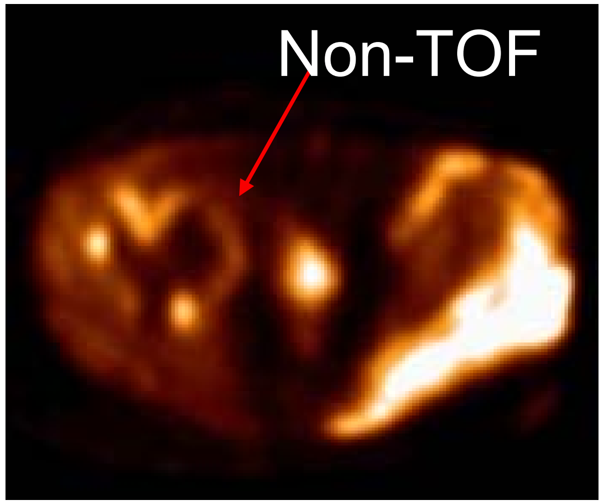
Time-of-Flight in PET

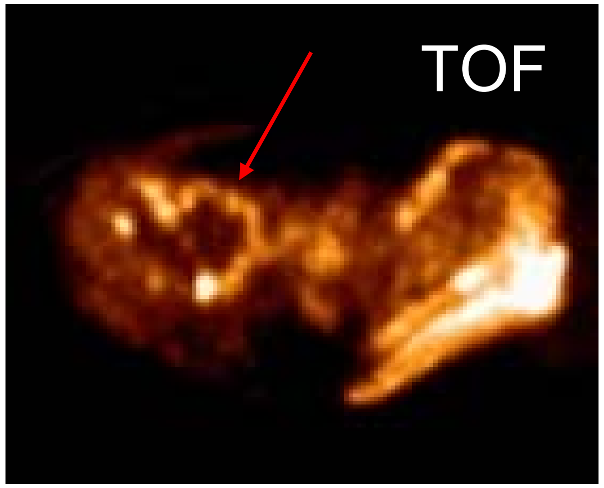


- Can localize source along line of flight.
- Time of flight information reduces noise in images.
- Variance reduction given by $2D/c\Delta t$.
- 500 ps timing resolution ⇒ 5x reduction in variance!

TOF (Effective Efficiency) Gain for Whole-Body PET (35 cm)

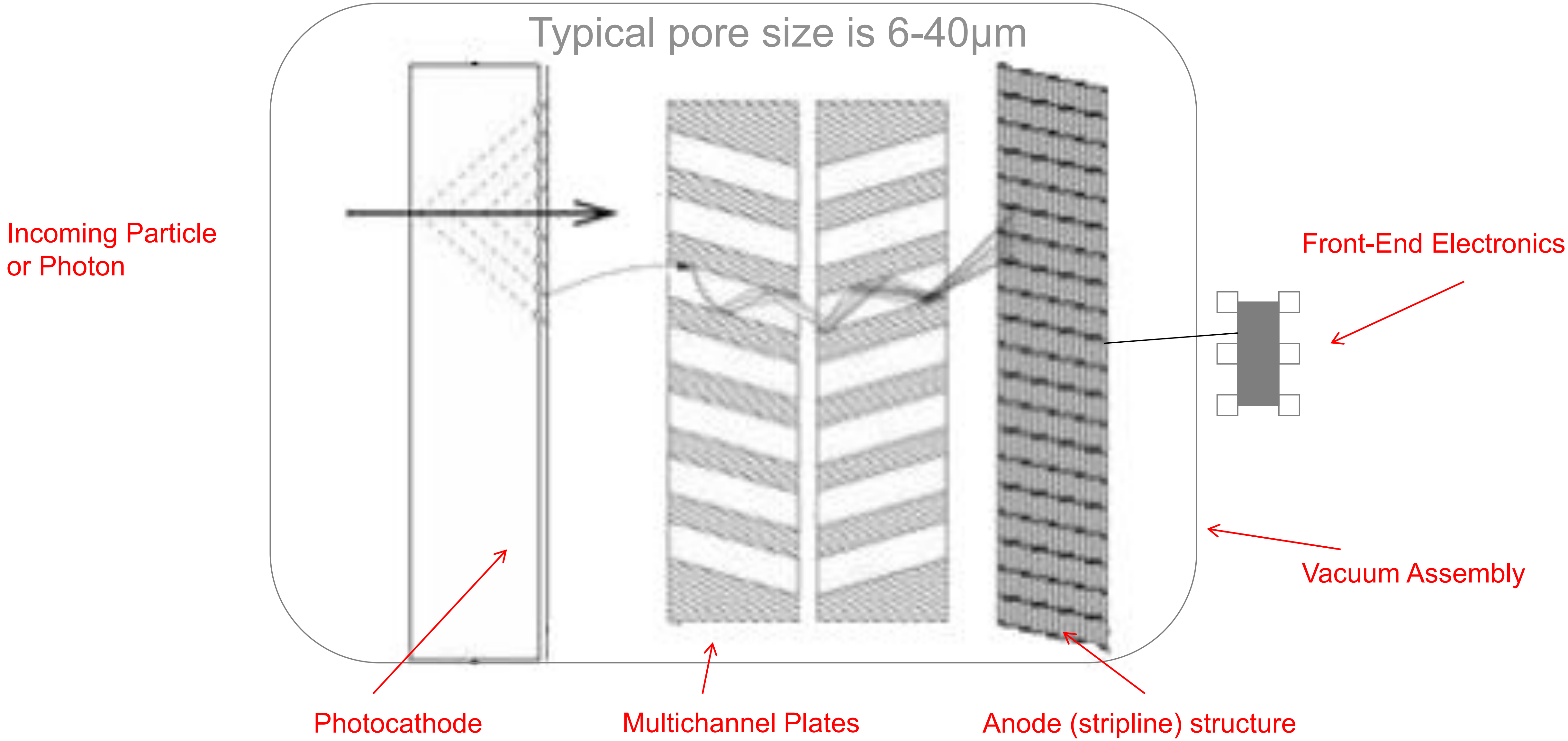
Hardware	Δt (ps)	TOF Gain
BGO Block Detector	3000	0.8
LSO Block (non-TOF)	1400	1.7
LSO Block (TOF)	550	4.2
$LaBr_3$ Block	350	6.7
LSO Side Coupled	250	9.3
LSO Small Crystal	210	11.1
LuI_3 Small Crystal	125	18.7
$LaBr_3$ Small Crystal	70	33.3





Bill Moses (LBNL)
Large Area Picosecond Photodetector Workshop,
Clermont-Ferrand, Jan 2010

Microchannel Plate Photomultipliers



Multiple plates to increase gain

Chevron arrangement to inhibit positive ion freeback to photocathode

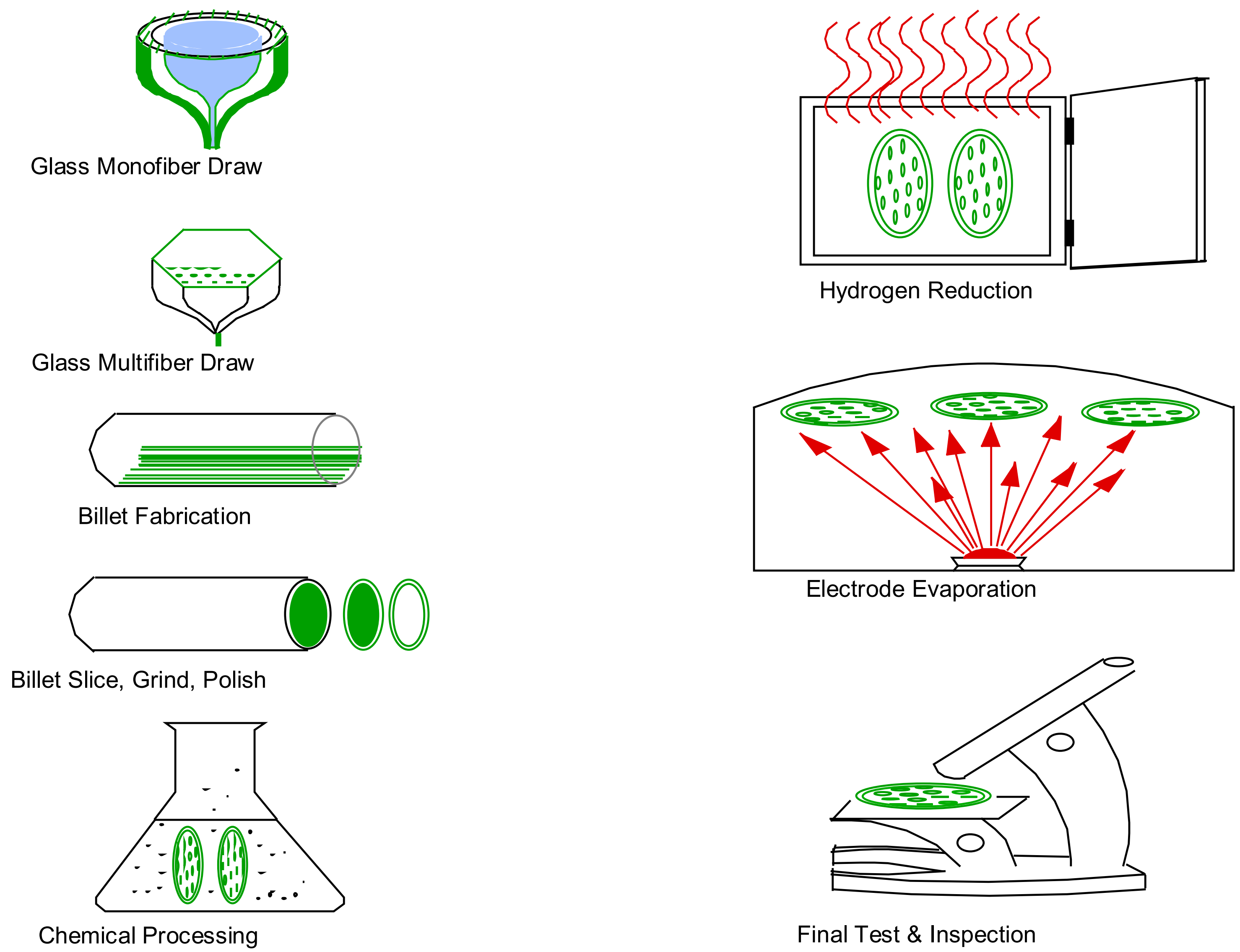
Commercial Microchannel Plate Fabrication

Graphic Credit: B. Laprade & R. Starcher, Burle (2001)

Glass is gravity-fed via cylindrical furnace

Glass is typically lead glass tube with solid soft glass core

Chemical processing to remove soft core glass

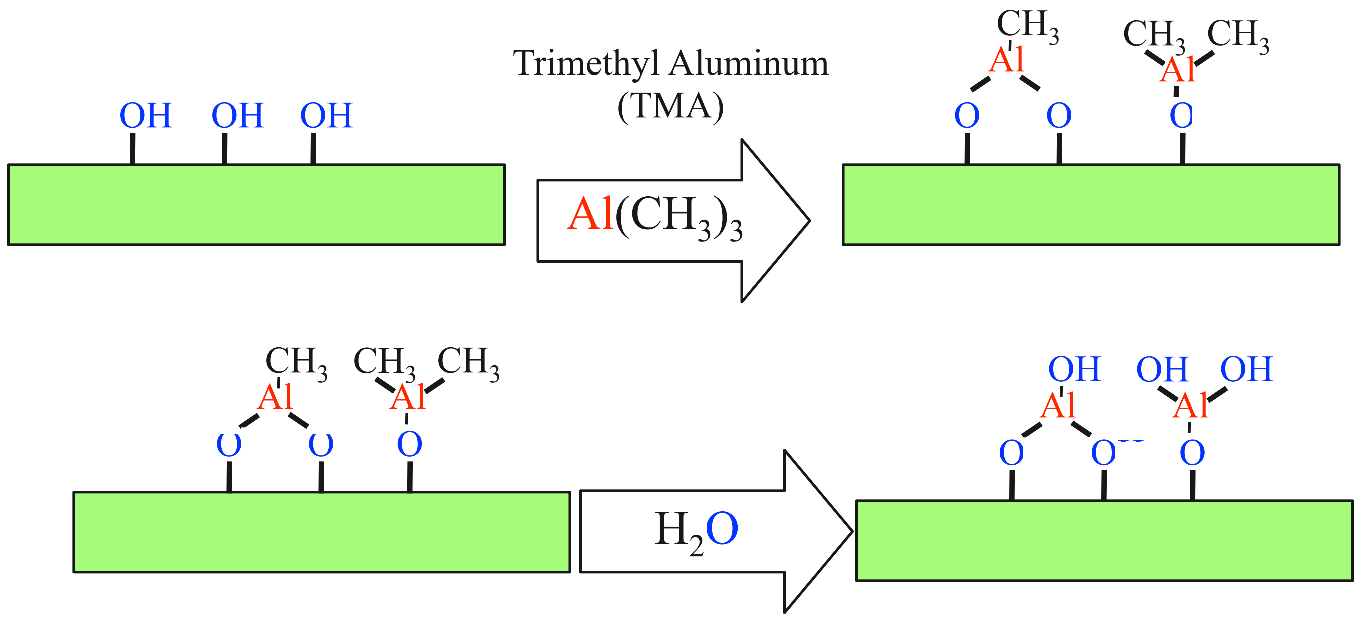


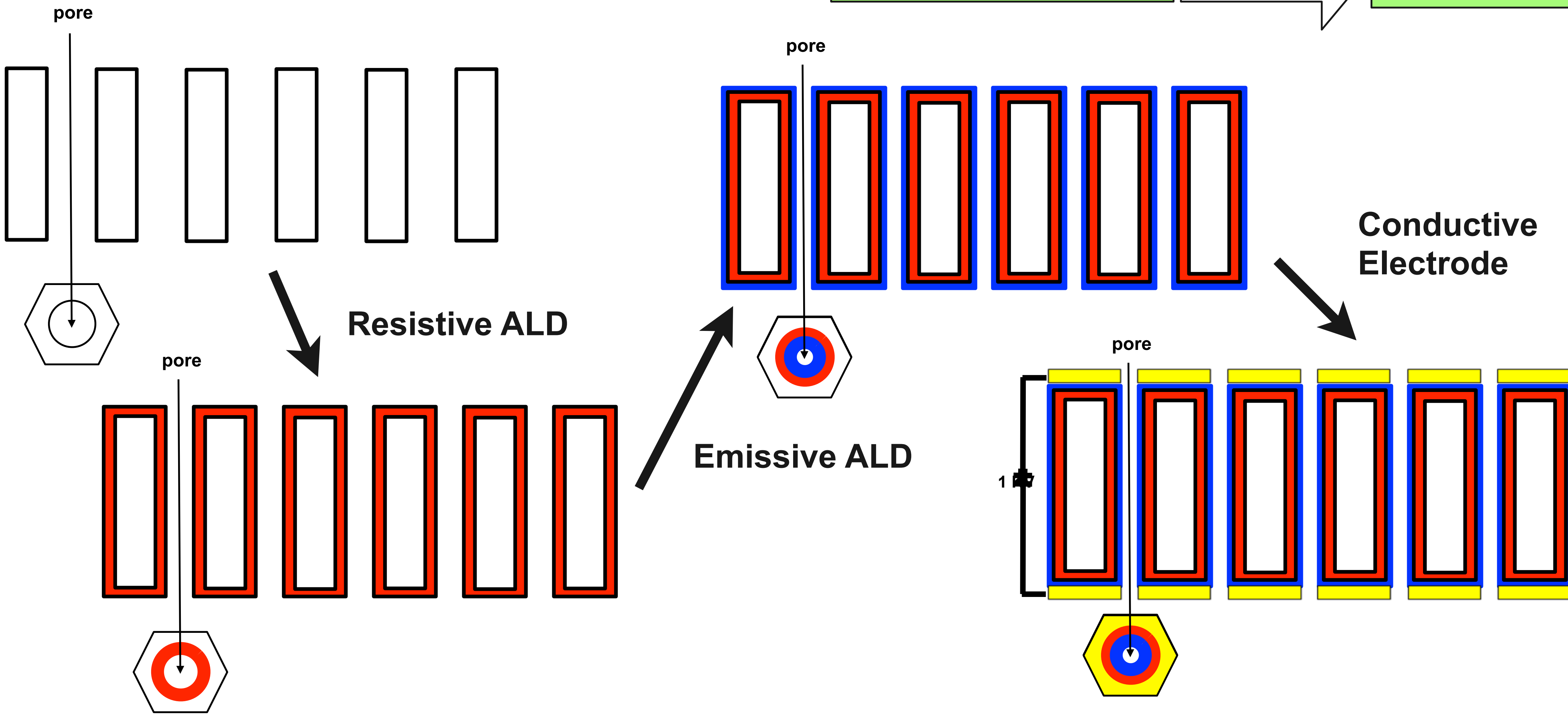
Before sealing in tube, plate must be subjected to prolonged exposure to electrons at low voltage to outgas H_2 and other material

Pore Activation via Atomic Layer Deposition (ALD)

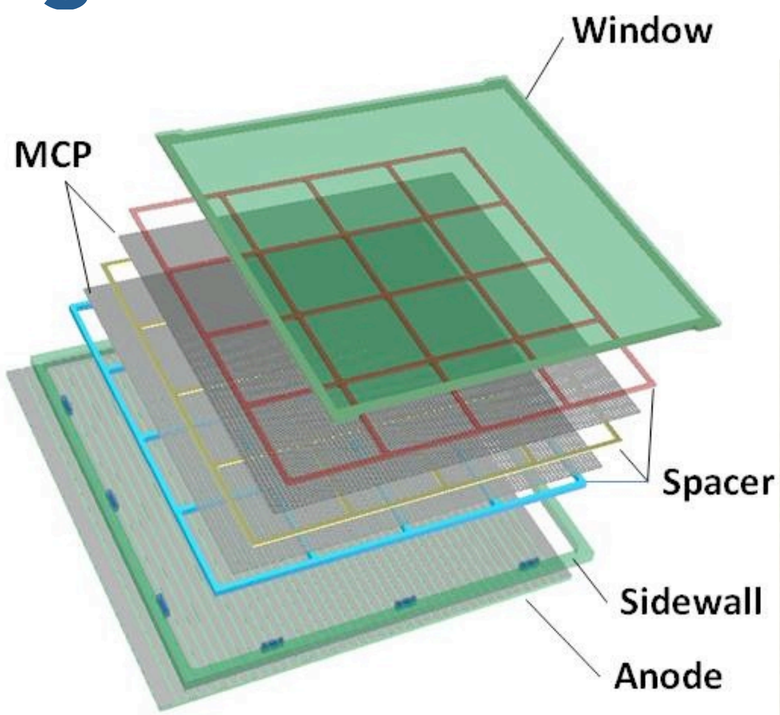
Example:

- OH on surface provide reaction sites
- Trimethyl aluminum reacts liberating methane, forms Al_2O_3 layer. Leaves methyl group inhibiting further reaction on surface
- Exposure to H_2O removes methyl group. Leaves OH sites for next reaction

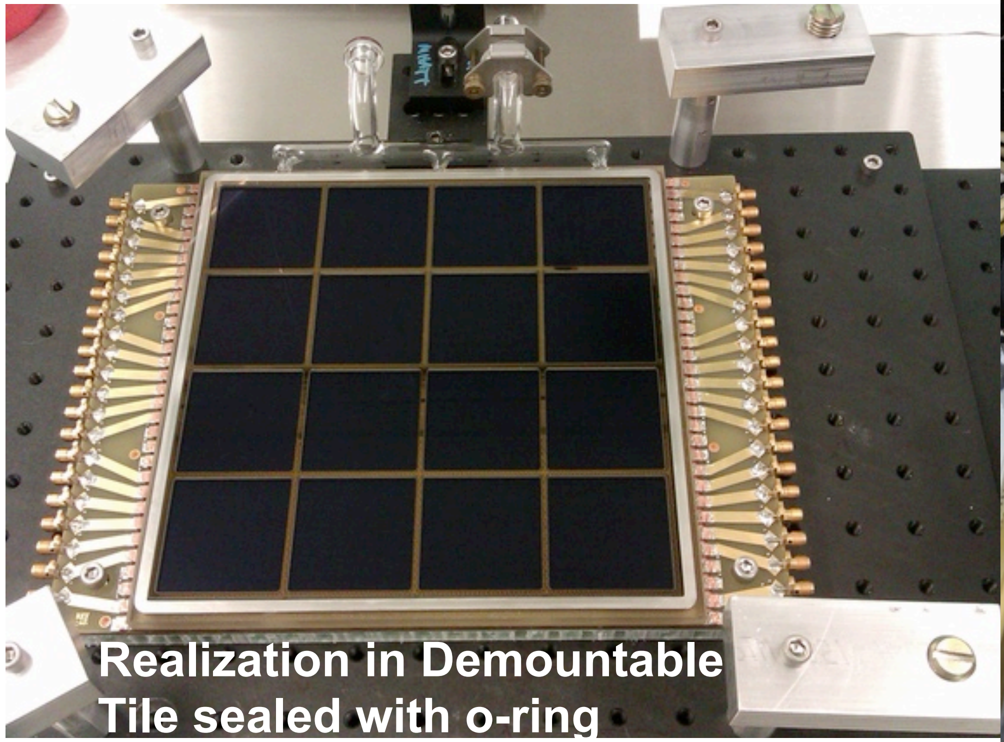




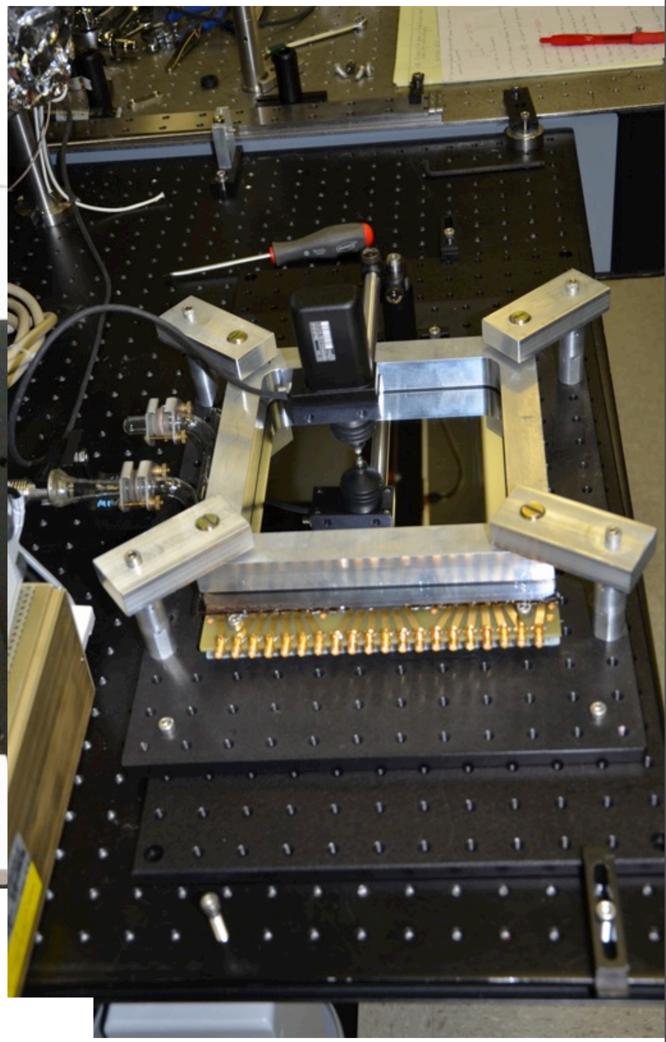
Concept of Lower Cost Borosilicate Glass Large Area MCP

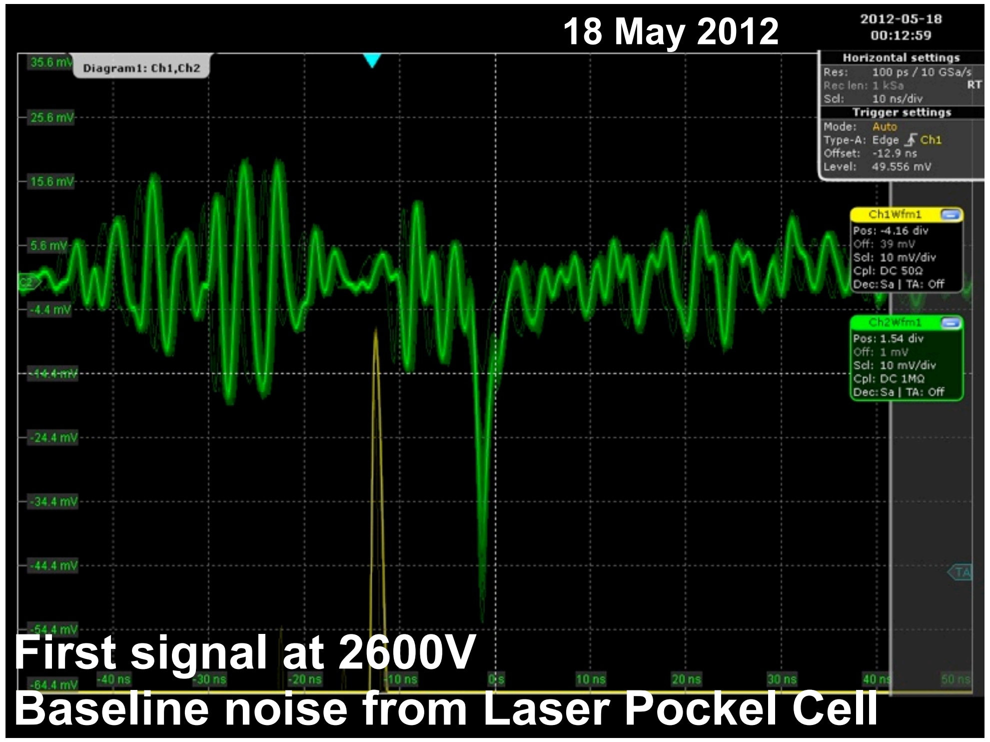


Design Drawing - September 2010

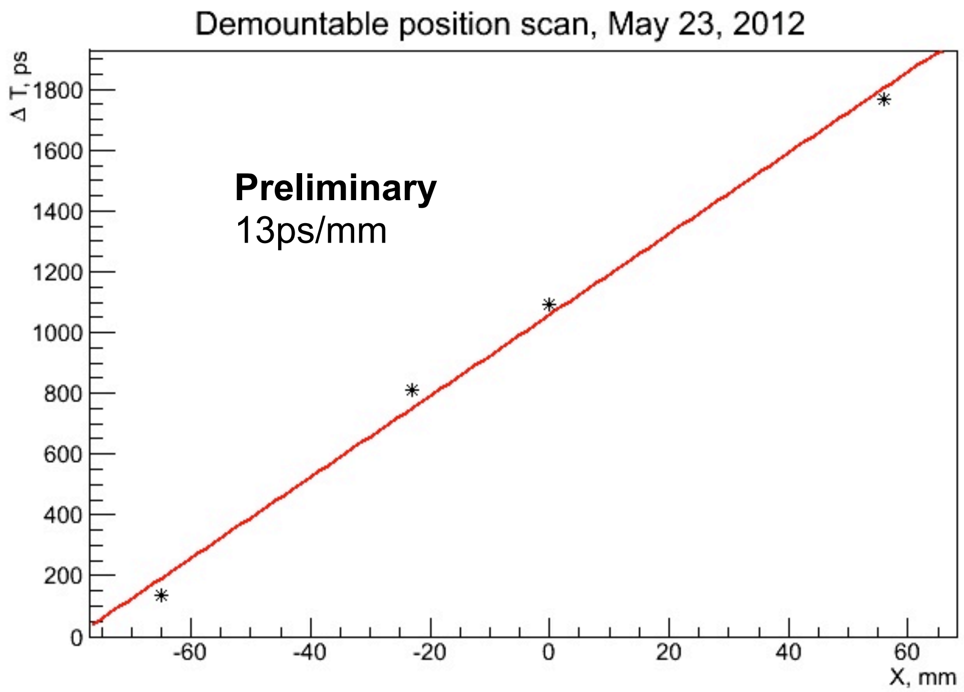


Realization in Demountable Tile sealed with o-ring



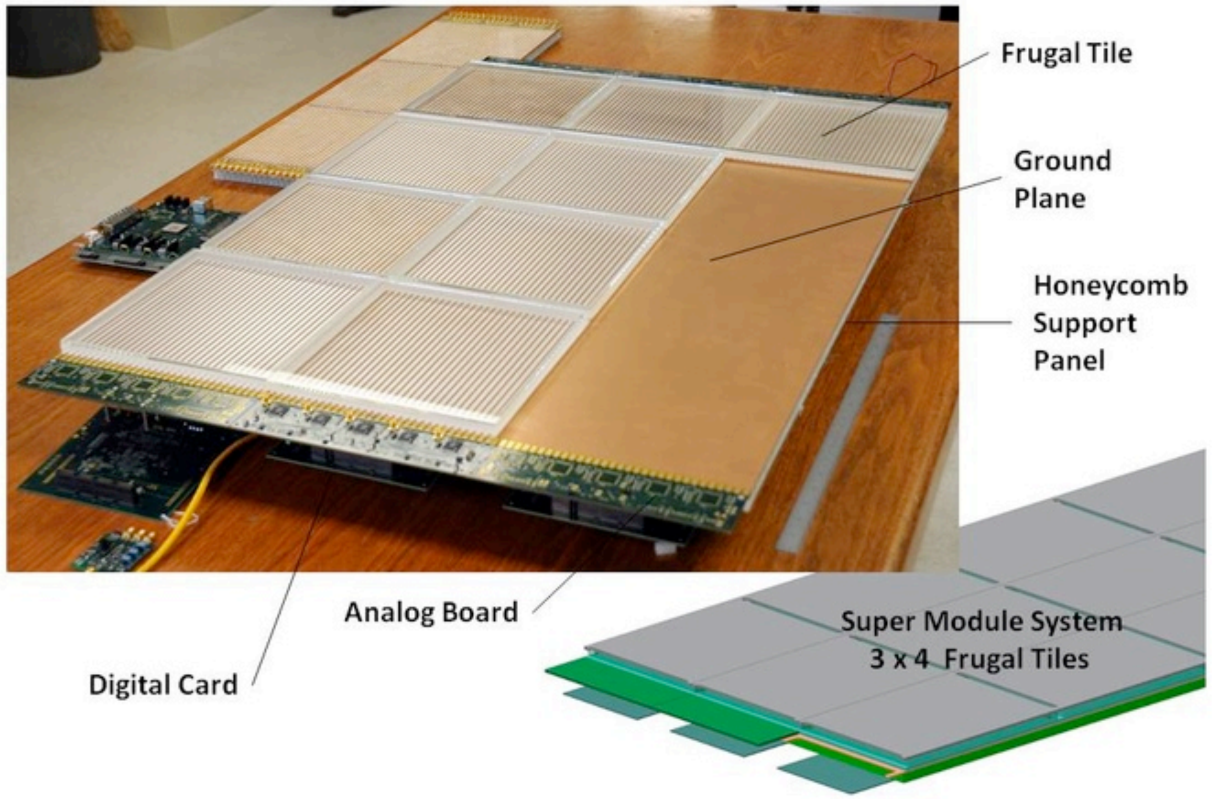


First signal at 2600V
Baseline noise from Laser Pockel Cell

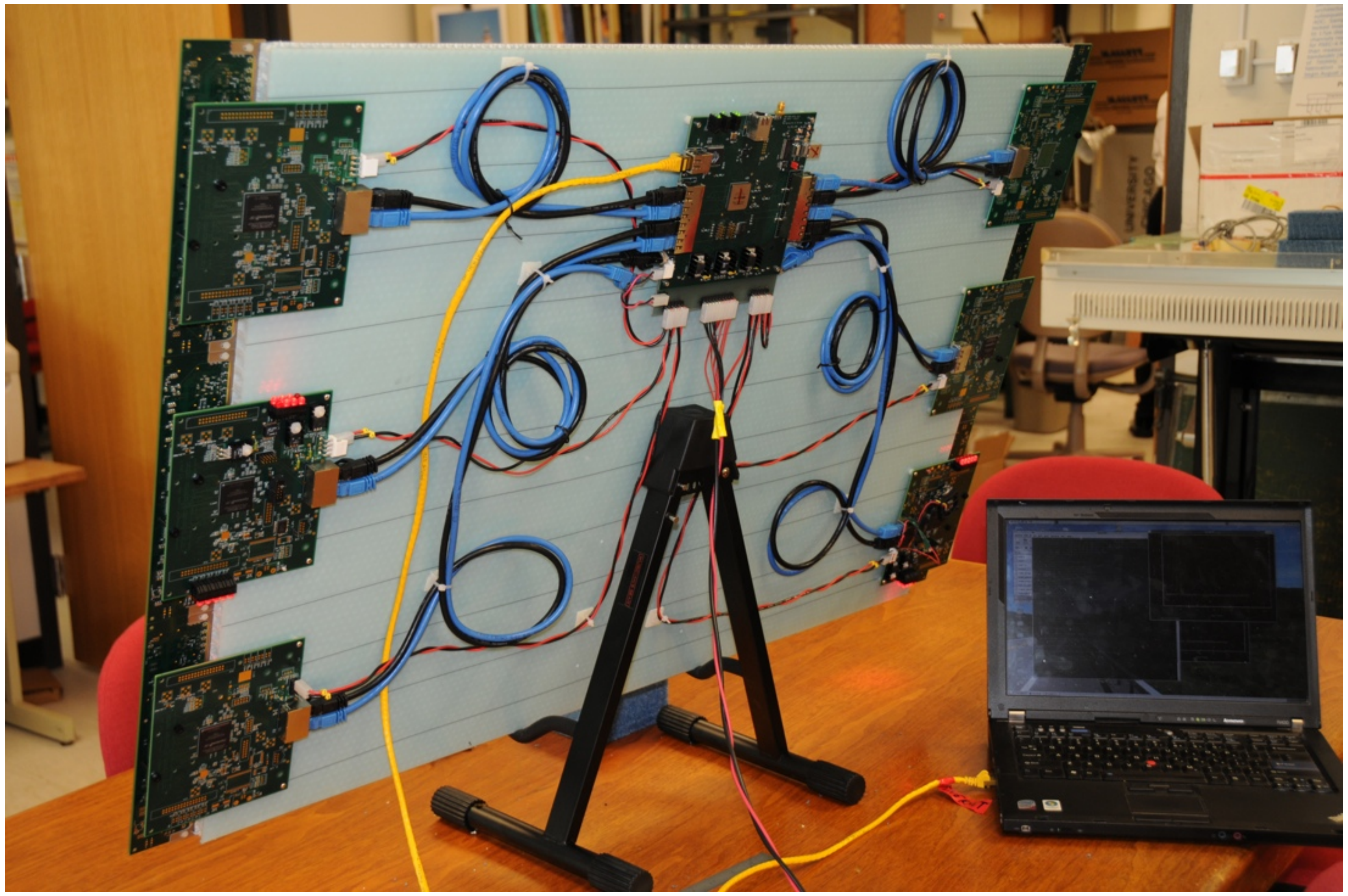


First Demountable Signals from UV laser excitation demonstrating whole of All-Glass Concept

Development of Panel Suitable for Water Cherenkov
The SuperModule



Tray and Tiles - The Super Module System



Complete readout chain ready from frontend waveform sampling ASIC through digital and central control cards to graphics processor PC

Planning for integration of readout chain into Demountable Tile Readout into "scope-in-a-box" ASIC into FPGA accomplished

Time Resolution vs. MCP Pore Size

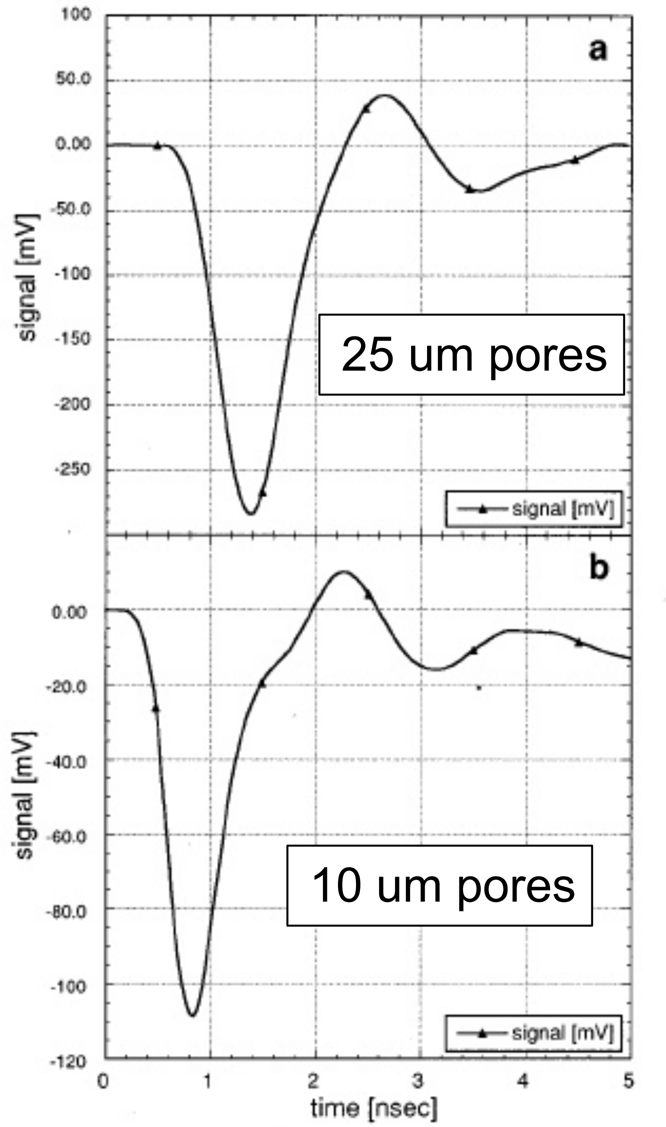
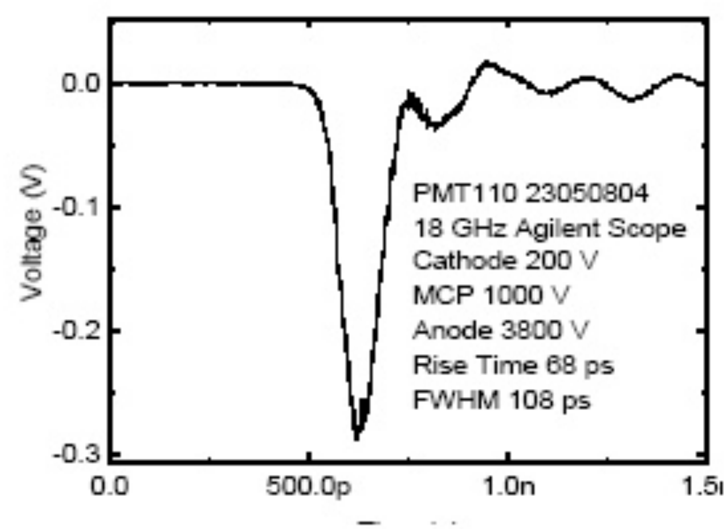
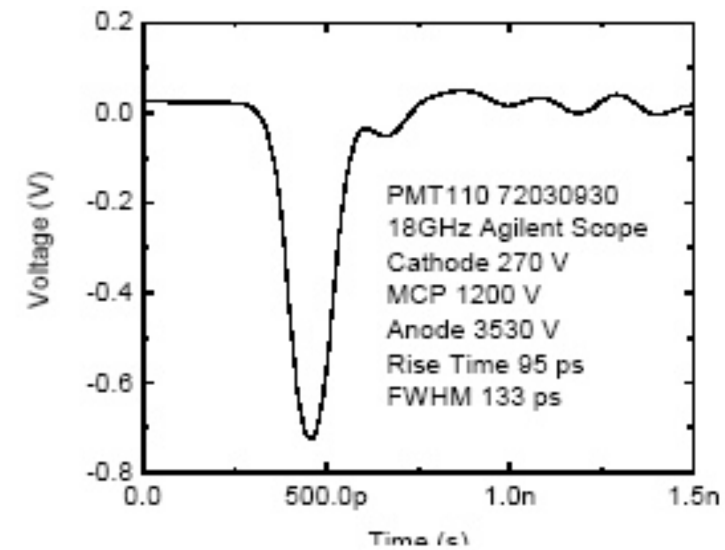


FIG. 3. Measured MCP response using channel plates with 25 μm pores [panel (a)] and with 10 μm pores [panel (b)]. The rise times are 433 and 335 ps, and the pulse widths are 739 and 582 ps, respectively.

Photek MCPs



3.2 µm pore MCP PMT

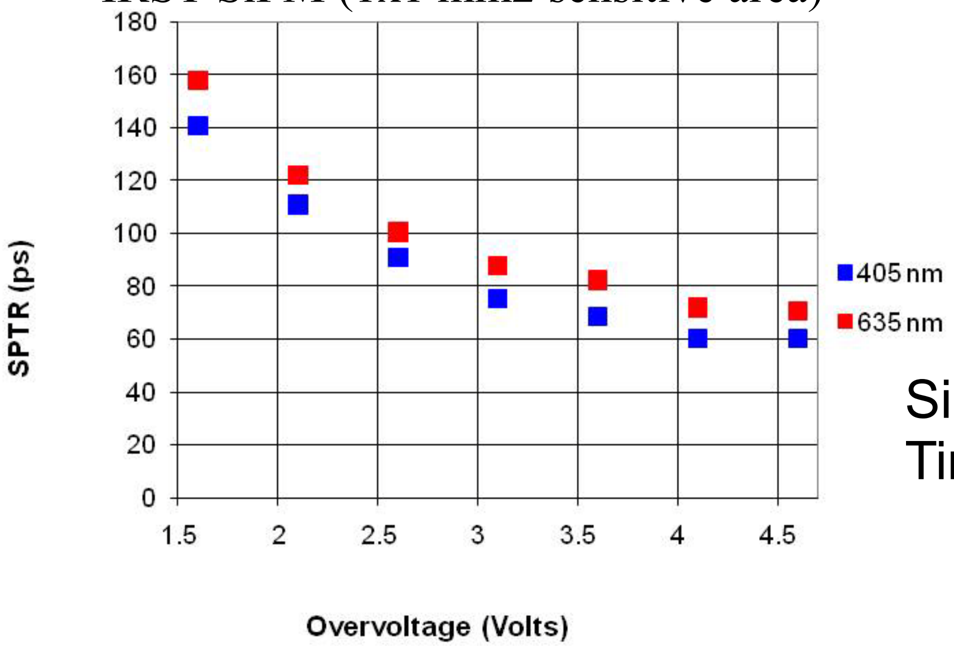


6 µm pore MCP PMT

Anton Tremsin (UCal-Berkeley/Arradiance, Inc.), Apr 2011
Factors That Limit Timing in Photodetectors Workshop
U. Chicago

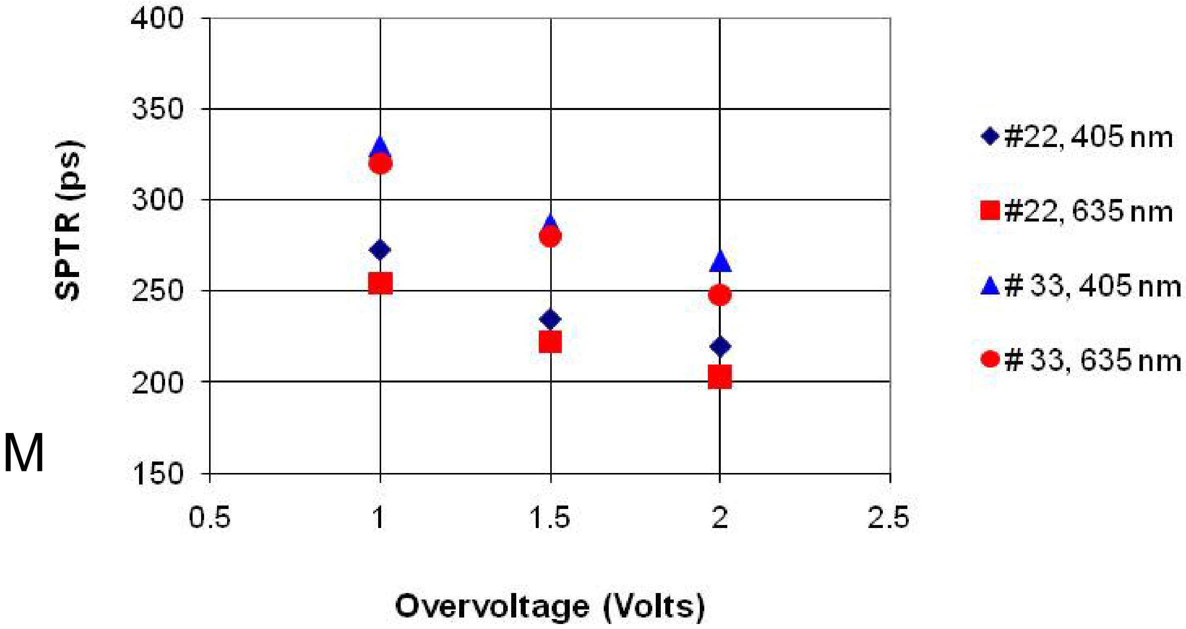
SiPM Timing Resolution

IRST SiPM (1x1 mm2 sensitive area)



Single Photoelectron Time Resolution of SiPM

Two MPPC samples (3x3 mm2 sensitive area)



Anatoly Ronzhin *et al.* (FNAL)
FERMILAB-PUB-10-052-PPD

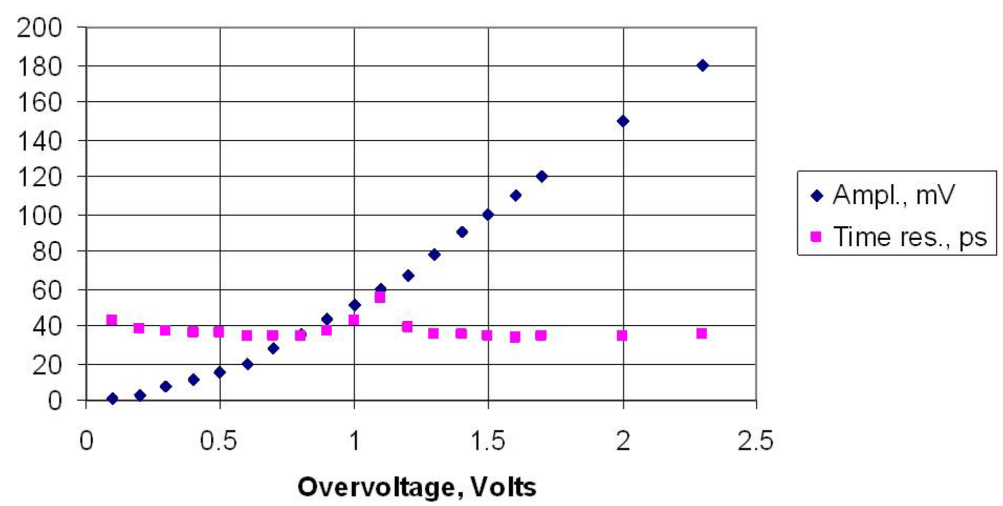
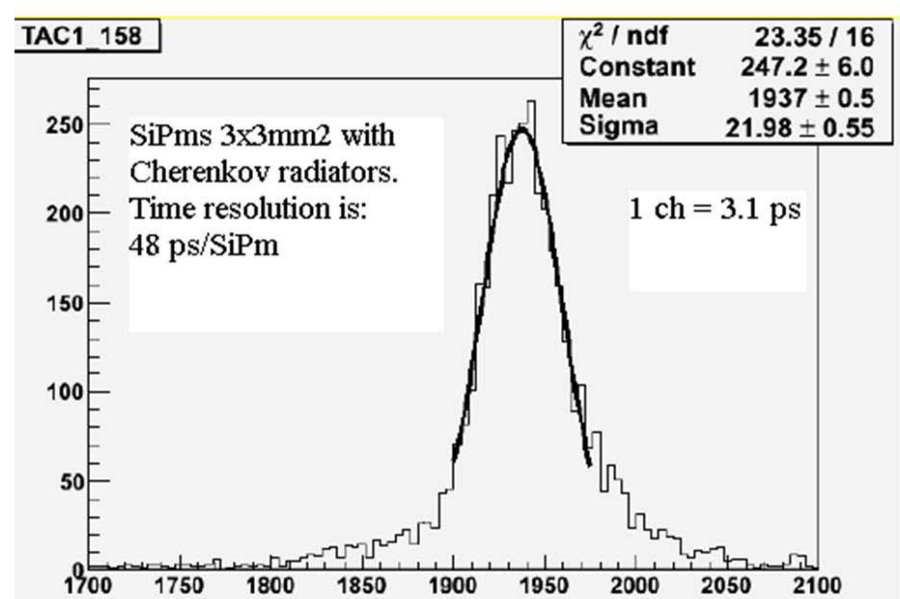


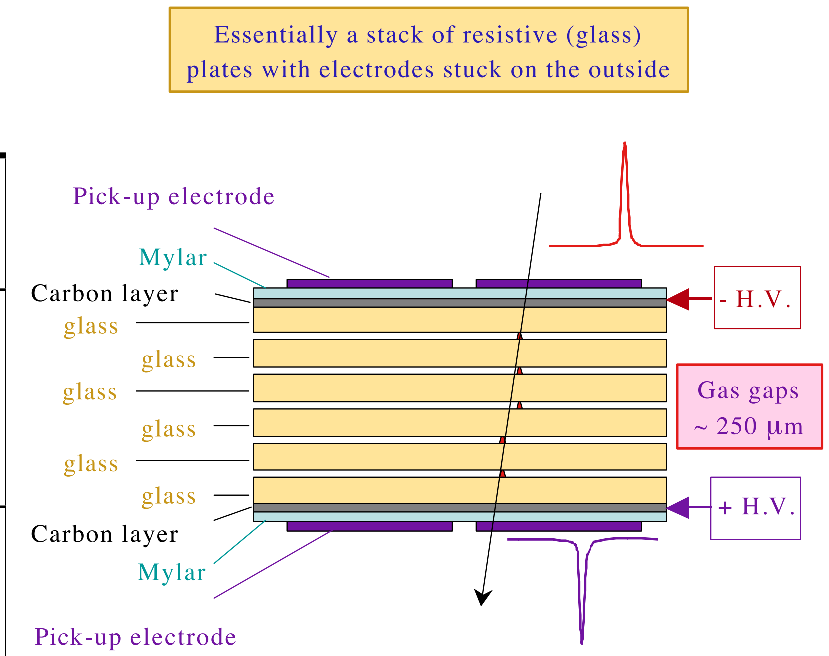
Figure 5. The MPPC signal amplitude and time resolution dependence on overvoltage for approximately 100 photoelectrons. A 20 db attenuator was placed inline at 1.2V overvoltage, showing the stability of the timing resolution using this method.

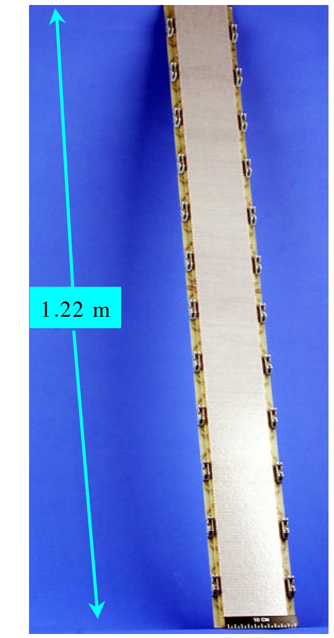


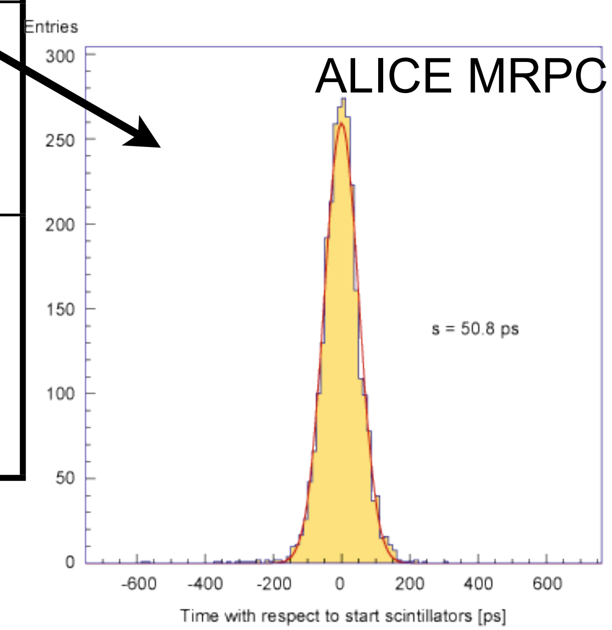
Time res. of 2 MPPC with Cherenkov radiators attached

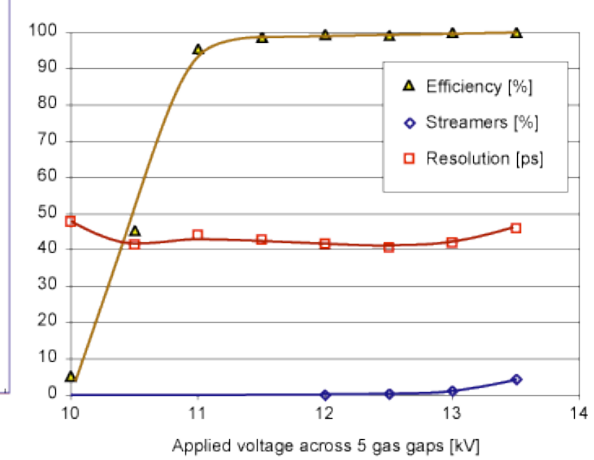
Limits on Timing Resolution in Gas Detectors

Detector Technology	Typical time resolution*
• Pestov Counter (High pressure, streamer discharge mode)	30-50 (ps)
• Resistive Plate Chambers (RPC) • MultiGap RPC	~ 1-5 ns (MIPs) ~ 50 ps (MIPs)
• Gas Electron Multiplier - UV photons - MIPs	~ 1-2 ns ~ 5-10 ns
• Micromesh Gaseous Structures - UV photons - MIPs	~ 700 ps ~ 1-10 ns









Maxim Titov (Saclay), Apr 2011
Factors That Limit Timing in Photodetectors Workshop
U. Chicago

Limitations of Electronics - Waveform Digitization

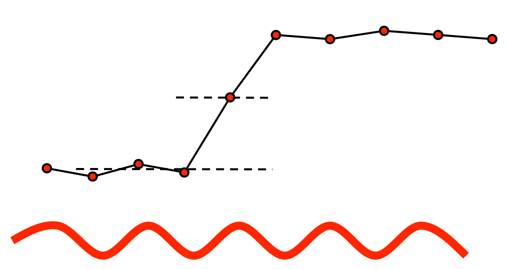
How is timing resolution affected?

$$\Delta t = \frac{\Delta u}{U} \times \frac{1}{\sqrt{3 f_s \times f_{3dB}}}$$

Assumes zero aperture jitter

	U	Δu	f_s	f_{3db}	Δt
today:	100 mV	1 mV	2 GSPS	300 MHz	~10 ps
optimized SNR:	1 V	1 mV	2 GSPS	300 MHz	1 ps
next generation:	100 mV	1 mV	20 GSPS	3 GHz	0.7 ps
next generation optimized SNR:	1V	1 mV	10 GSPS	3 GHz	0.1 ps

includes detector noise
in the frequency region of the rise time
and aperture jitter



Stefan Ritt (PSI), Apr 2011
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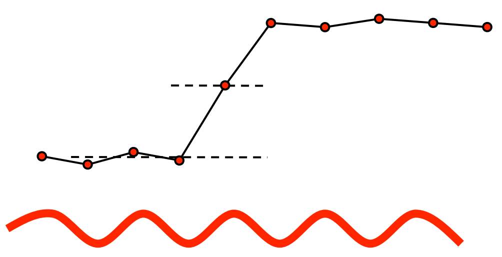
How to achieve this?



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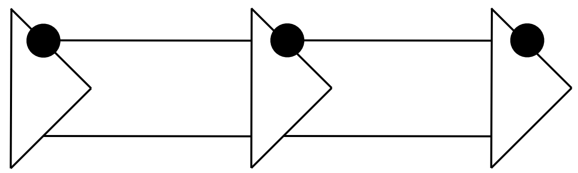
Stefan Ritt (PSI), Apr 2011
Factors That Limit Timing in Photodetectors Workshop
U. Chicago

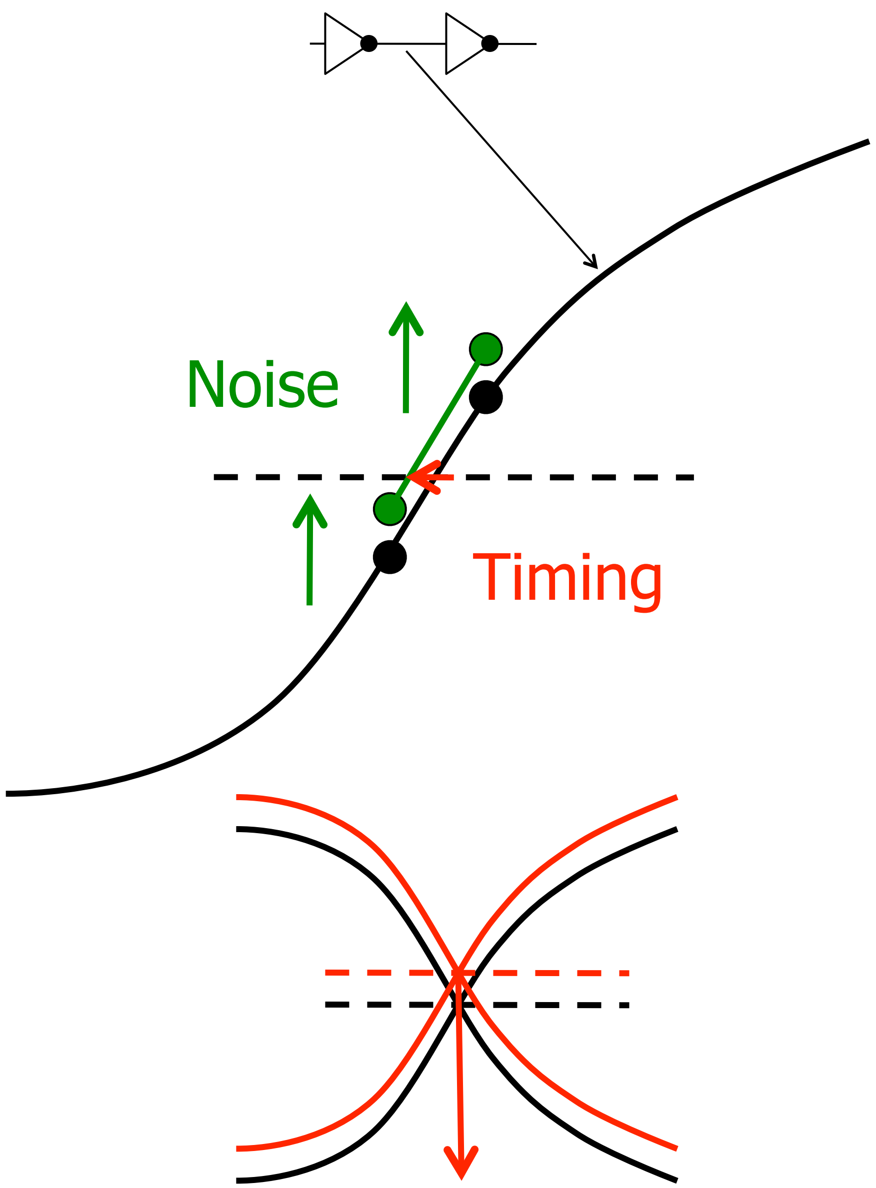
Timing Workshop, Chicago April 28th, 2011

Limitations of Electronics - Noise

Residual aperture jitter

- V_{dd} (GND) noise causes jitter
- Effect worse if rise time is slow (starving)
- Typical values:
  - 100 ps rise time for 1.2 V signal
  - 5 mV noise
  - 32 cells
  - Jitter: 5 mV/1.2 V * 100 ps * 32 = 13 ps
- Noise can originate off-chip (e.g. running ADC)
- Solution: Differential inverters, LDO on chip
- Disadvantage: More power





Stefan Ritt (PSI), Apr 2011
Factors That Limit Timing in Photodetectors Workshop
U. Chicago

Timing Workshop, Chicago April 28th, 2011

PXPS2012 TOF Parallel Sessions

Sat. June 16

1. Intro & Overview — M. Albrow
2. Timing needs and possible technologies for mu-egamma and mu-eee — F. DeJongh
3. Development of timing detectors for ATLAS Forward Protons — A. Brandt
4. QUARTICs for CMS/HPS — M. Albrow

Precision Timing Will Be Important Component of Project X Beam & Experiments.

Expect ample time for discussion

Please join us!

Mon. June 18

1. Timing performance of MCPs fabricated using atomic layer deposition — A. Elagin
2. Fermilab test beam facility and timing detector development — E. Ramberg
3. SiPM studies for fast timing — A. Ronzhin (tbc)
4. Ultrafast lasers for beam timing — V. Scarpine
5. Time of Flight in n-nbar search: needs and capabilities — Y. Kamyshkov
6. Other (tbc)
7. Future directions discussion, does a plan emerge? — ALL